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PROPERTIES OF NEARLY PERFECT CRYSTALS AT VERY LOW TEMPERATURES

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Background

Precision clocks are instruments of wide applicability, and play a role in the measurement of many fundamental quantities in physics and astronomy. Current time standards are based on atomic clocks which have frequency stabilities of parts in 10^{14} or 10^{15}, depending on the averaging time of the measurement. Averaging times on the order of seconds to hours are typical for this level of precision. Significant tests of gravitational physics could be conducted with a satellite-borne precision clock with a frequency stable to parts in 10^{17} or 10^{18}. In particular, a second-order test of the general relativistic gravitational redshift could be conducted with such a clock on board a satellite in earth orbit. Also, a measurement of the sun's mass quadrupole moment could be made with a clock in a solar orbit. Since orbital time scales would be involved in such experiments, the relevant averaging time would be on the order of months.

Clocks on board spacecraft need to be small and self-contained. A high quality low temperature quartz crystal is one potential oscillating system which might be suitable for precision clocks of required stability. Smagin has reported a Q of 4×10^9 for a quartz crystal oscillator at 2 K[1]. It is possible that even higher Q's would be obtained at lower temperatures. With a Q of 10^9, a frequency stability of 10^{-17} would require dividing the linewidth to 1 part in 10^8. In principle, this can be achieved by cooling to low enough temperature, using enough power in the oscillator, and integrating for a long enough time.

However, drift of the central mode frequency can degrade oscillator performance, and one of the advantages of using cryogenic temperatures is an improved drift performance over a room temperature oscillator. Irreversible effects such as internal motion of impurities and lattice defects, and the adsorption of surface contaminants can be made arbitrarily small with sufficiently low temperatures. Komiyama, and Robichon et. al. have also reported appropriately low temperature coefficients for mode frequencies.[2,3] In principle, therefore, state-of-the-art temperature control can reduce central-frequency thermal drift to the required level.

To this end, an investigation of the properties of high quality quartz crystals was undertaken with a view to determining their suitability as a time standard.

Experimental

An experimental test of drift performance on a time scale of days was carried out as follows. Five commercially prepared precision AT-cut crystals were obtained from Colorado Crystal Corporation.[4] Each crystal came mounted in a hermetically sealed glass case, evacuated except for some residual helium exchange gas included to prevent thermal gradients along the length of the crystal. The crystals were suspended from opposite edges by their electrical leads attached to metal posts. The third vibration mode at 5 MHz was excited.

Two crystals at a time were mounted in a liquid helium dewar, with the outer glass envelopes in direct contact with the cryogenic bath. The dewar was shielded with liquid nitrogen so that thermal leaks were kept to a minimum. With this arrangement, the helium bath boiling rate was quite low, and the experimental space was vibrationally quiet. The helium charge would last a few days, with the experiment kept at 4.2 K for the duration of this time.

Each crystal was excited with a driving circuit shown in Fig. 1. This circuit was designed by the University of Maryland Physics Department Electronic Development Group and contains a gallium-arsenide FET preamp in close proximity to the crystal which works at low temperatures. The outputs from both crystals were combined in a mixer, and the resultant beat frequency formed a measure of the differential drift rate. The beat frequency was typically less than 100 Hz.

Figures 2 - 4 show the beat frequency drift as a function of time for crystals #39 and 40. The beat frequency shift is relative to the average beat frequency during the course of the measurement. At each time the beat frequency was sampled repeatedly, and the error bars show the fluctuations in these samplings. Roughly speaking, there is an order of magnitude improvement in the frequency drift between room temperature and 4.3 K. Figure 2 shows the room temperature fluctuations with unbalanced deviations on the order of $\Delta\nu/\nu \sim \pm 5 \times 10^{-8}$. This figure is improved at 77 K (Fig. 3) to $\sim \pm 1 \times 10^{-8}$. At 4.3 K (Fig. 4) we have $\Delta\nu/\nu \sim \pm 5 \times 10^{-9}$.

Conclusions

The data of Figs. 2 - 4 show that the frequency stability of 5 MHz AT-cut quartz crystal oscillators is improved by lowering the temperature to 4.3 K. The resultant level of stability is apparently not, at this point, sufficient for a clock accurate to 1 part in 10^{17}. However, many improvements are possible in the scheme presented here. These would involve better temperature regulation, better crystal mounting and vibration isolation, and lower temperatures. Below the λ-transition at 2.17 K the residual bubbling of the bath would be eliminated. Thus, the prospect of a successful clock built on this scheme is not ruled out.

References

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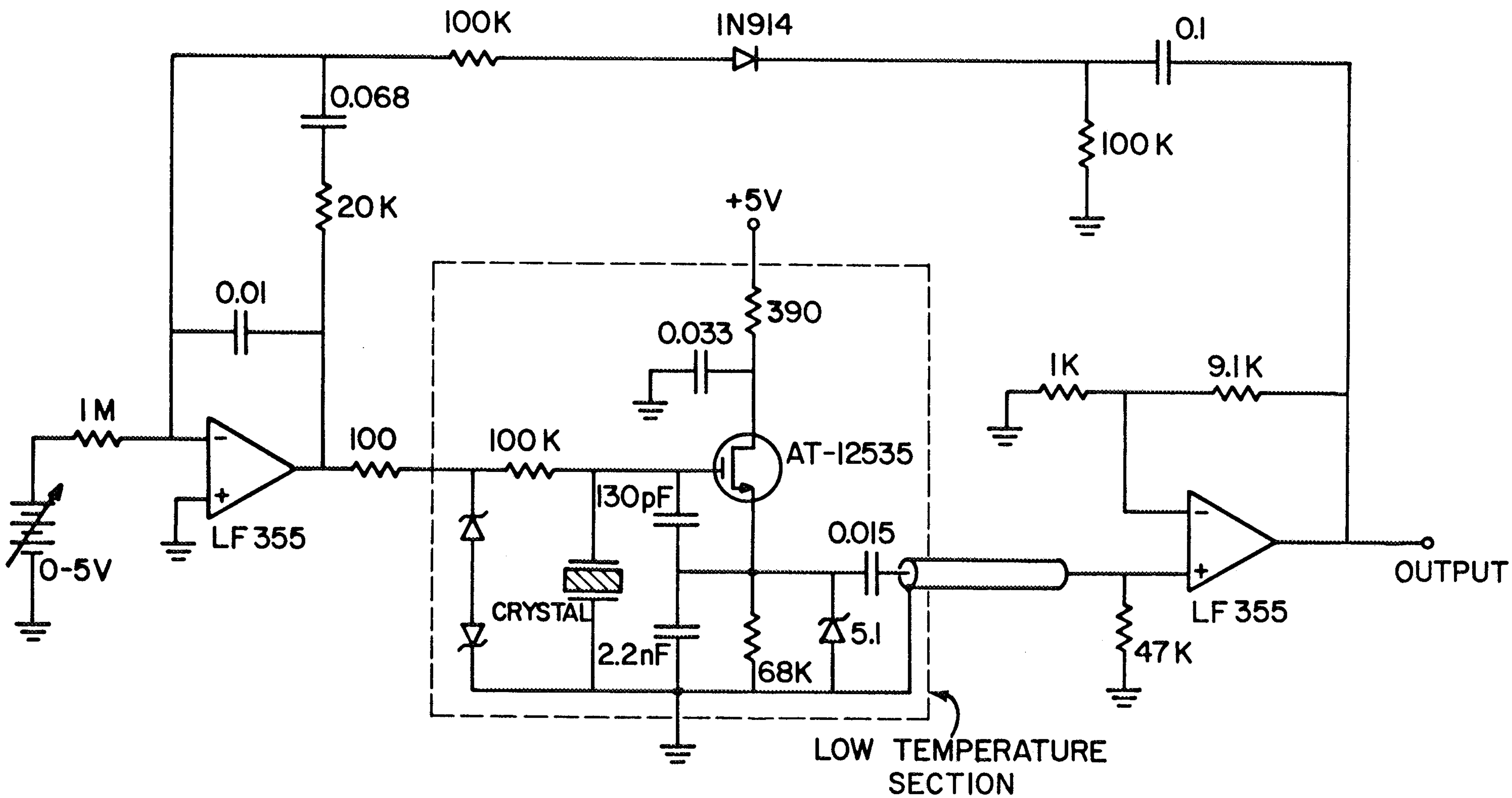
(3.) G. Robichon, J. Groslambert, and J. J. Gagnepain, *Proc. 38th Symp. on Frequency Control*, 201 (1984).

(4.) Colorado Crystal Corporation, Loveland, Colorado.



100K
IN914
0.1
0.068
100 K
20 K
+5V
0.01
390
0.033
1K
9.1K
1M
100
100 K
AT-12535
130pF
0.015
0-5V
LF355
CRYSTAL
2.2nF
68K
5.1
47K
LF355
OUTPUT
LOW TEMPERATURE SECTION

Fig. 1

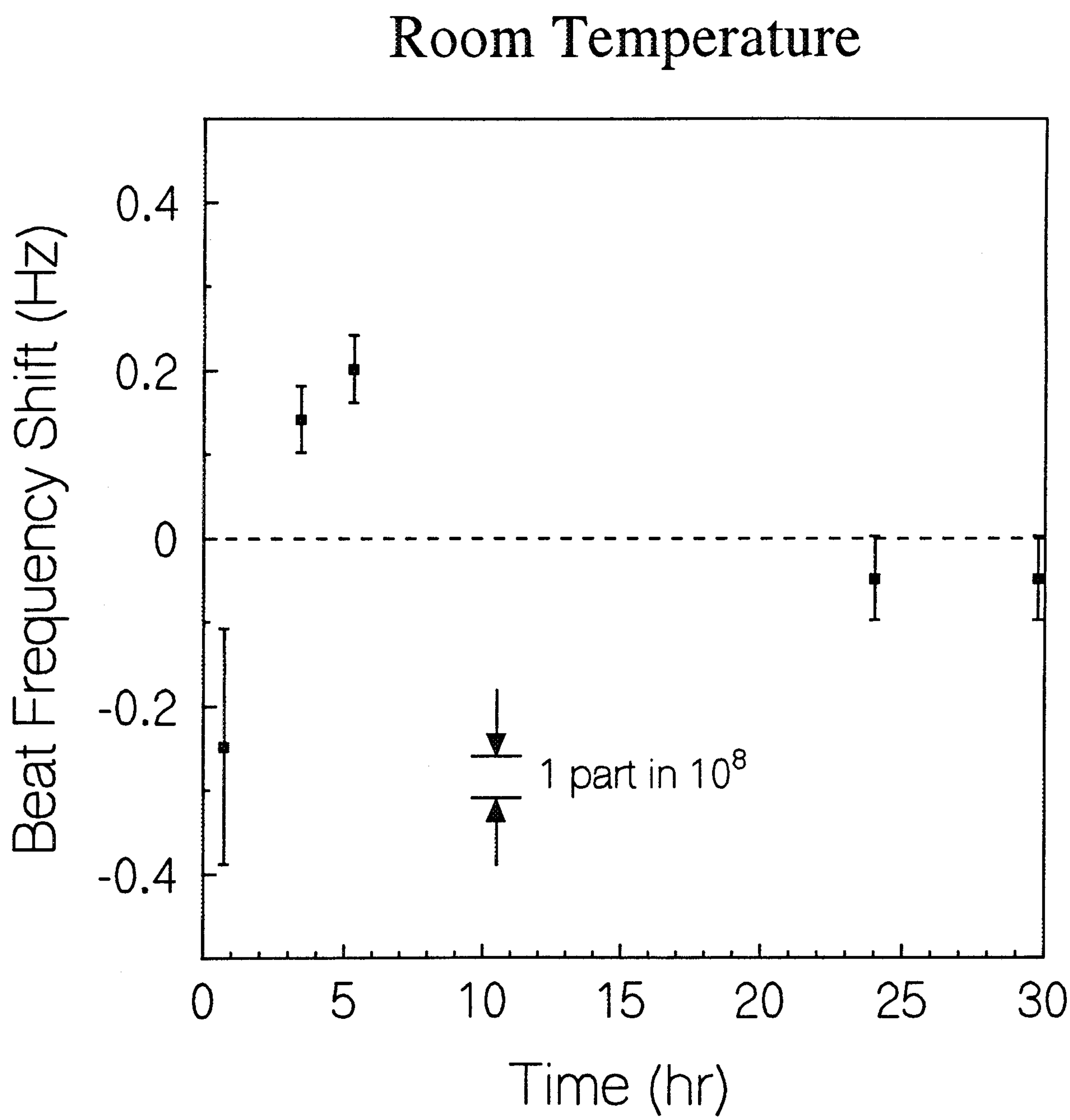
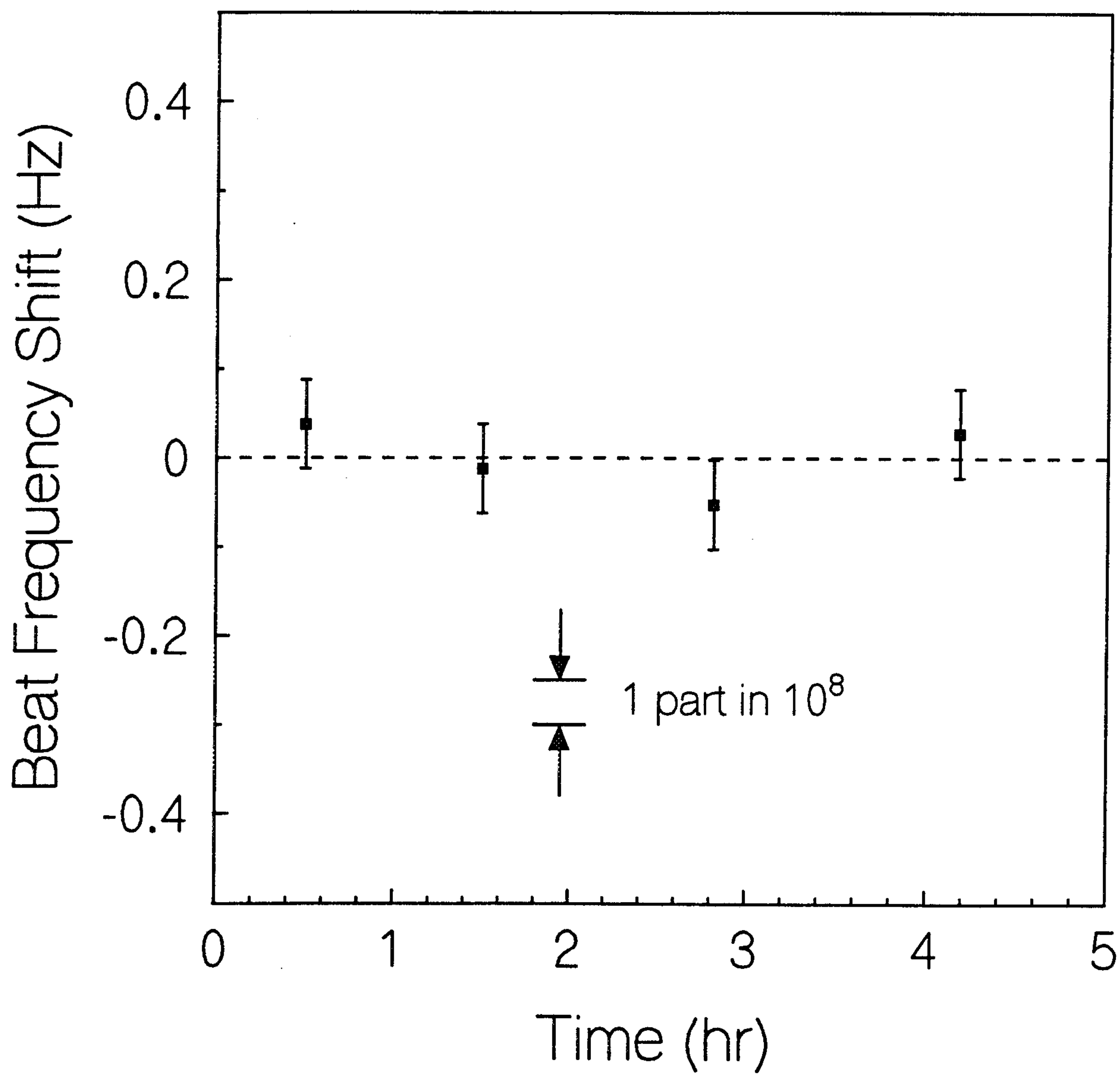

Room Temperature
Beat Frequency Shift (Hz)
0.4
0.2
0
-0.2
-0.4
1 part in 10^8
0
5
10
15
20
25
30
Time (hr)

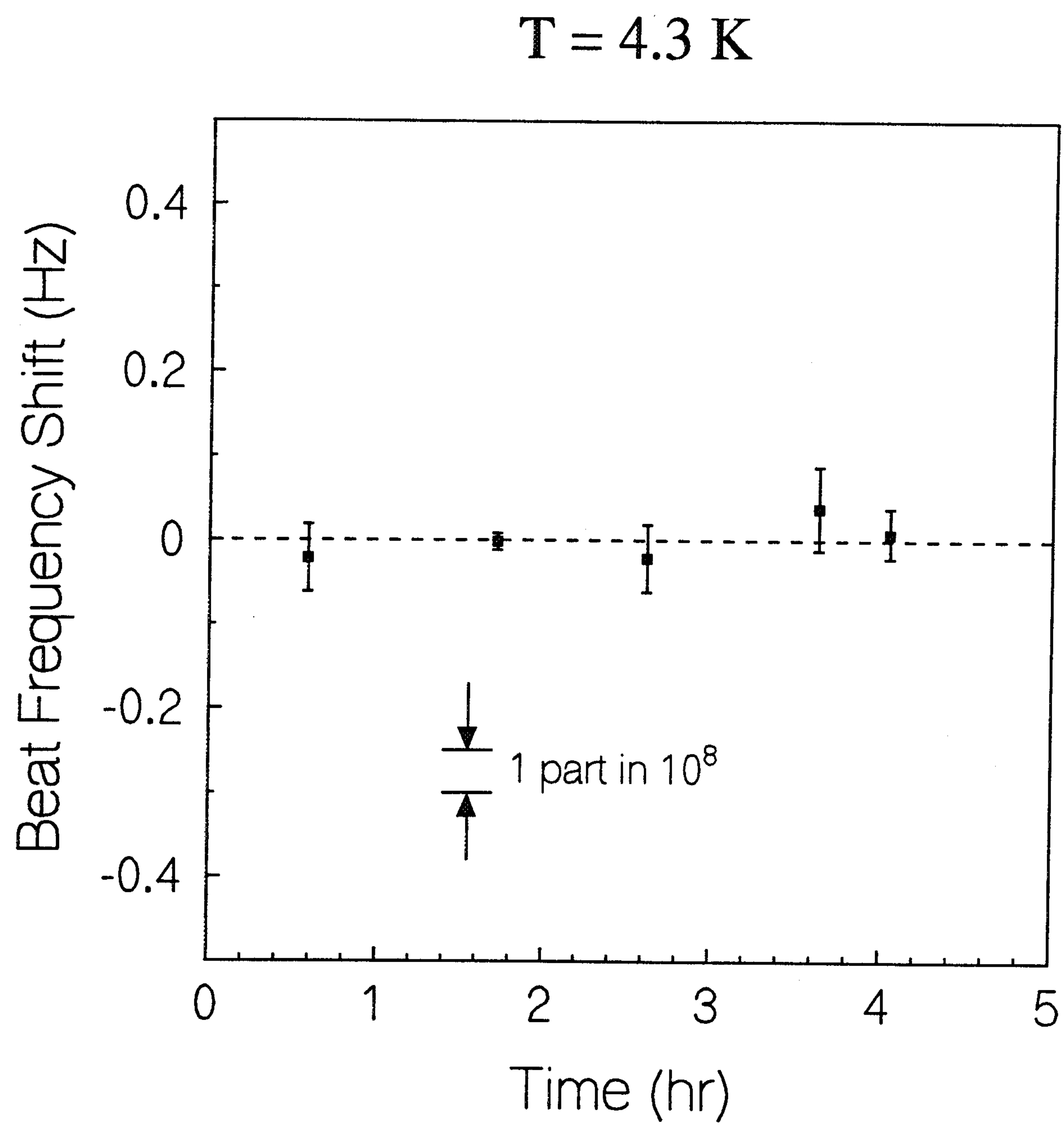
Fig. 2

T = 77 K



0.4
0.2
0
-0.2
-0.4
Beat Frequency Shift (Hz)
1 part in 10^8
0
1
2
3
4
5
Time (hr)

Fig. 3



T = 4.3 K
Beat Frequency Shift (Hz)
0.4
0.2
0
-0.2
-0.4
1 part in 10^8
0
1
2
3
4
5
Time (hr)

Fig. 4